Low-Resolution TV: Subjective Comparison of Interlaced and Noninterlaced Pictures

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A subjective comparison of line-interlaced television pictures and non-interlaced television pictures has shown that the line-interlacing of low-resolution television pictures provides a bandwidth saving of considerably less than 2:1 when the line structure of the picture is visible.

A 2:1 line-interlaced television picture was subjectively compared with several noninterlaced television pictures in an effort to determine their subjective equivalency in terms of bandwidth. Several other variables—noise, spot-wobble, line-width to line-pitch ratio, different models, illumination and luminance—were also employed in the experiments. The televised pictures consisted of a head-and-shoulder view of a model pantomiming a two-way conversation.

The results indicate that the line-interlacing of low-resolution television pictures provides about a 37 percent saving in terms of bandwidth at a relatively low value of high-light luminance of 40 fL (140 cd/m^2) and as little as a 6 percent savings at a high-light luminance of 100 fL (340 cd/m^2). When the line-width to line-pitch ratio is set at its preferred value for all pictures, a significant difference is obtained when the high-light luminance is decreased from 60 fL (200 cd/m^2) to 40 fL (140 cd/m^2). The effects of Gaussian noise, spot-wobble, illumination, and different types of models did not alter the subjective equivalence of line-interlaced and noninterlaced television pictures significantly. The addition of noise to a spot-wobbled picture was found to be more detrimental to the quality of the noninterlaced pictures than to the line-interlaced picture.

I. INTRODUCTION

The lower limit of the picture repetition rate for television pictures is dictated by the critical-fusion frequency (CFF).[1,2] The CFF is approximately proportional to the logarithm of the luminance over a wide range. It is also approximately proportional to the logarithm

of the size of the flickering area. The CFF is on the order of 60 pictures per second for present day television luminances and picture sizes.

The television engineers of the 1930's experimented with two-fold line-interlaced pictures as a means of saving bandwidth. In two-fold line-interlaced pictures, alternate lines are scanned during successive vertical deflection cycles. Engstrom[3] found that the vertical deflection cycle should be greater than 50 Hz and should be a multiple of the power line frequency. In 1941 the National Television System Committee (NTSC)[4] adopted a vertical deflection frequency of 60 Hz for two-fold line-interlaced commercial broadcast systems. Two-fold line interlace has since been adopted by virtually all television systems, regardless of the application.

One-half of the lines in a line-interlaced television picture are scanned during alternate half-cycles of the frame rate which is 30 Hz. The result is essentially two light pulses for each frame period, i.e., an apparent rate of 60 light pulses per second. Thus, large-area flicker is negligible if present at all.

When all of the lines except one of a line-interlaced television raster are masked that line appears stationary and nonflickering. When all of the lines except two of a line-interlaced television raster are masked the two lines appear to jump back and forth as if in motion. When the masking is removed the whole raster appears to shimmer. When a picture is reproduced on the raster the shimmering is confined to small isolated areas of roughly equal brightness. The shimmering effect in these areas is most pronounced at brightness boundaries. This phenomena of apparent-motion is due to the out of phase relationship between adjacent lines of the raster and appears to be affected by the same laws as flicker. These apparent-motion defects are called interline flicker by the television industry.

Engstrom[3] found that interline flicker was visible at the same distance at which the line structure becomes visible. His conclusion was that the observer must be seated at a distance equal to or greater than that distance at which the line structure becomes resolvable.

Line crawling is another subjective defect associated with line-interlaced pictures. This stroboscopic defect takes the form of an apparent crawling of the lines either up or down depending on which direction the eye tends to track. Line crawling is related to the perceptibility of interline flicker and becomes increasingly perceptible with increasing picture brightness and angle subtended by the eye of adjacent line centers.

A third defect inherent to line interlaced pictures is subjective line-

pairing. Subjective line-pairing produces the same subjective impression as physical line-pairing, i.e., when adjacent lines are physically superimposed on each other by the deflection circuitry. Subjective line-pairing occurs when either the televised image or the observer's visual center of attention moves in a direction other tban parallel to the scanning lines. This defect also occurs when the observer blinks his eyes or effectively strobes the picture. Subjective line-pairing is most evident when the motion is parallel to the vertical scan direction and at a rate equal to the field rate.

The question arises, "Do the degrading effects associated with interline flicker nullify the advantage of being able to present twice as much information in each picture when the line sturcture is visible"? Accordingly three suhjective experiments were conducted in an attempt to answer this question.

The experiments were conducted on low-resolution television pictures. In the first experiment, a 225-line interlaced picture was compared with four noninterlaced pictures ranging from a 225-line picture to a 135-line picture in steps with ratios of $\sqrt[4]{2}$. Additional variables at two values each—noise, illumination, spot-wobble, and picture material—were also introduced. Two types of observers, skilled and nonskilled, were used.

The second experiment was performed in order to determine the effects of a change in luminance on the subjective relationsbip between the interlaced picture and the noninterlaced pictures. Five noninterlaced pictures were compared with the 225-line interlaced picture starting with a 189-line picture and decreasing in steps with ratios of $\sqrt[8]{2}$ to a 135-line picture. The subjective relationship between the noninterlaced pictures was also investigated.

For the third experiment, the preferred line-width to line-pitcb ratio was determined in a separate experiment. In this experiment, tbe line-width to line-pitch ratio was set at the preferred value for each picture. The 225-line interlaced picture was compared with 5 noninterlaced pictures starting at a 225-line picture and decreasing to a 147-line picture in steps with ratios of $\sqrt[8]{2}$. Two levels of luminance were introduced as a second variable.

The bandwidth in each of the above cases was adjusted such that the vertical to horizontal resolution ratio was approximately 1:1.[6] A-B testing techniques were used. Each A-B pair consisted of the interlaced picture and one of the noninterlaced pictures except for that portion of the second experiment where the noninterlaced pictures were compared against each other.

II. TEST APPARATUS

The basic operation and layout of tbe test apparatus is illustrated by block diagrams shown in Figs. 1 and 2.

Fig. 1 illustrates tbe basic functions of the counting and sync signal generating apparatus. The vertical counting and vertical sync generating apparatus was held constant for all picture rates. The vertical sweep rate was 60 Hz. Two sets of horizontal counters were used. The counters were programmed to produce the desired line rate by opening and closing appropriate leads witb remote controlled relays. The proportion of the horizontal blanking period to the line period was kept constant for all rates at $\frac{1}{6}$ of the line period. The vertical blanking period was held constant at $\frac{1}{10}$ of the field period.

The ratio of the vertical divisor to horizontal divisor was an integer for the noninterlaced pictures. The ratio of the two divisors was an integer plus one-half for the interlaced picture.

Fig. 2 illustrates the basic operation of the rest of the test apparatus.

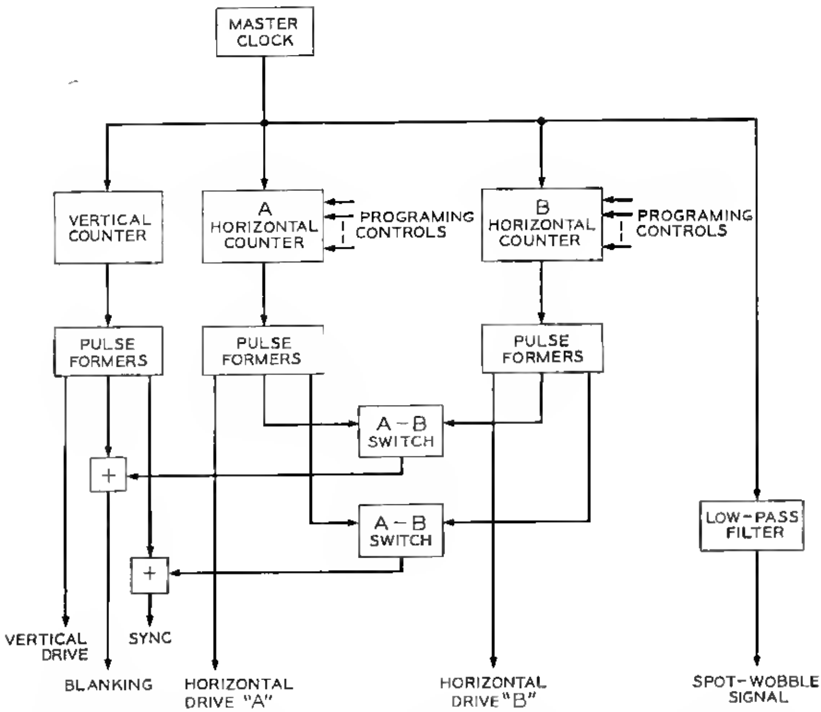


Fig. 1 — Simplified block diagram of sync generator and pulse forming apparatus.

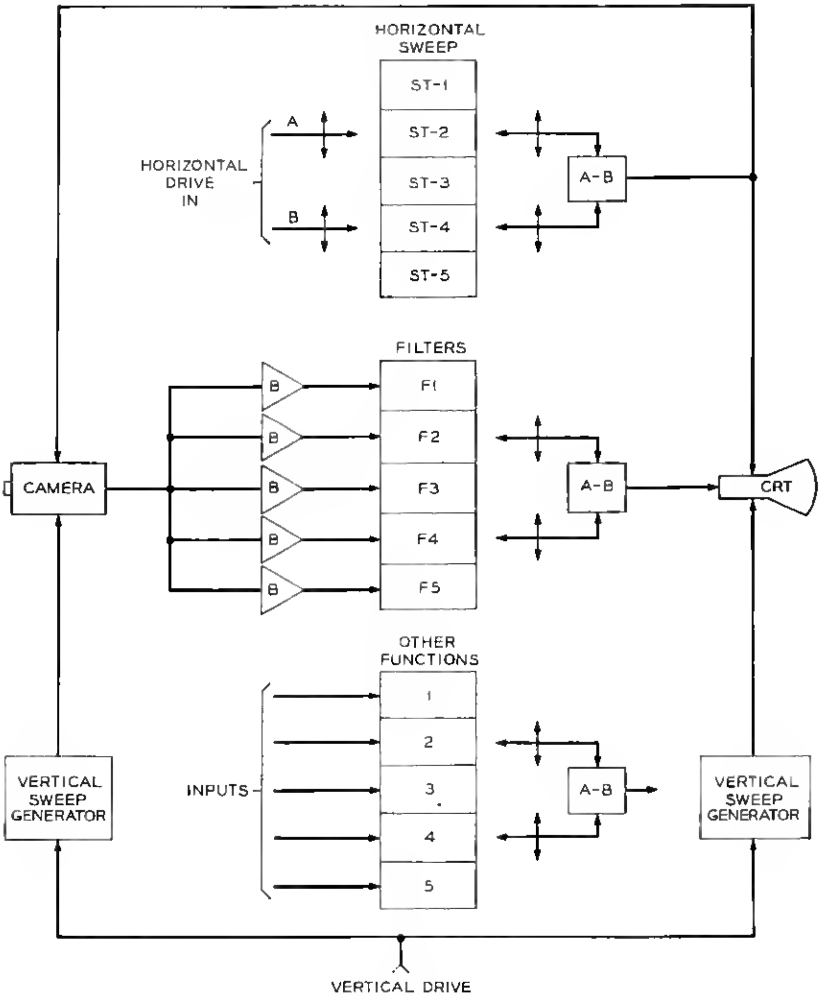
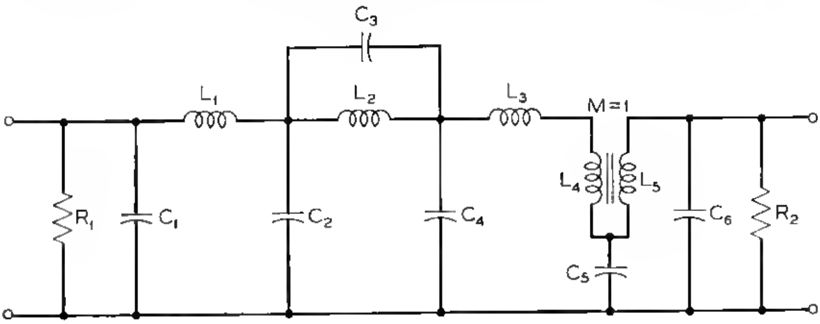


Fig. 2 — Simplified block diagram of test apparatus.

An RCA TK-21 camera chain was the core of the camera end of the test apparatus. Six horizontal sawtooth generators were used to accommodate six different sweep rates. These were carefully designed driven circuits which provided a sweep linearity on the order of ± 1 percent of full scale deflection. Remote-controlled relays were used to preselect the two sawtooth signal generators. The two sawtooth signals for driving both camera and monitor sweeps were then applied to an A-B switch which selected the desired one of the pair.

Great care was taken in the design and construction of the sweep and associated circuits to insure that line spacing on the pick-up tube and display tube was correct in all cases.

Six low-pass filters were provided for processing the picture signals of the six different sweep rates. The filters were isolated from each other with buffer amplifiers. The appropriate filter for each sweep rate was selected by remote-controlled relays. Each filter had an ad-



(a)

$fd = f_{co}/1.57$	$R_2 = 0.3257\,R_1$
$L' = \dfrac{R_1}{0.952\,fd}$	$C' = \dfrac{1}{0.952\,R_1\,fd}$
$L_1 = 0.1195\,L'$	$C_1 = 0.04709\,C'$
$L_2 = 0.1600\,L'$	$C_2 = 0.1581\,C'$
$L_3 = 0.1303\,L'$	$C_3 = 0.03189\,C'$
$L_4 = 0.0357\,L'$	$C_4 = 0.4856\,C'$
$L_5 = 0.05568\,L'$	$C_5 = 1.438\,C'$
	$C_6 = 0.1292\,C'$

(b)

Fig. 3 — Low-pass filter: (a) circuit diagram, (b) design data.

justable attenuator which permitted balancing for the difference in insertion losses.

Each filter had a near Gaussian roll-off, had linear phase, and exhibited a preshoot and overshoot in its step response.* The preshoot and overshoot were each 12 percent of the step-signal amplitude. The cutoff frequency for the filters was arbitrarily selected as the -20-dB point on their response curve. Fig. 3 shows the circuit configuration and design data for the filter.† Fig. 4 shows the typical amplitude

* An earlier experiment (unpublished) indicated subjectively that this type of filter gave the preferred picture rendition.

† Designed by G. Szentermai of Bell Telephone Laboratories, Incorporated.

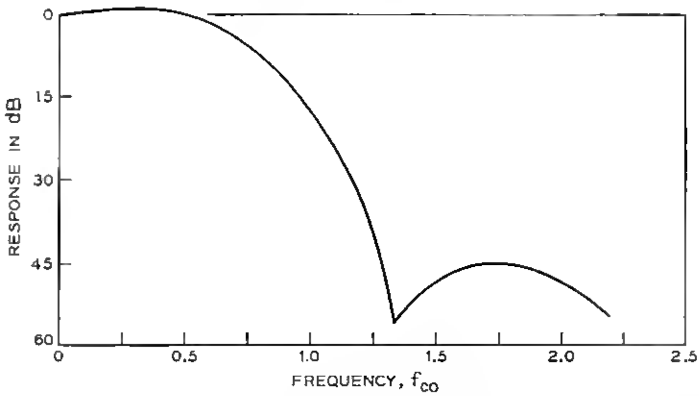


Fig. 4 — Relative amplitude versus frequency response characteristics of low-pass filter.

versus frequency characteristics of these filters and Fig. 5 the typical step response. After adjustment of the effective vertical resolution by applying a Kell factor of 0.7 and allowing for the difference between vertical and horizontal blanking periods, the cutoff frequency (-20 dB) of the low-pass filters was selected to provide approximately equal horizontal and vertical resolution.[5]

Three other functions were selected and switched in much the same manner. These were spot-wobble, line-width to line-pitch ratio and camera raster centering. Each of these functions had its individual balancing controls.

The spot-wobble signal was a 7.1442-MHz sine wave locked to the master clock. The spot-wobble signal was applied to the picture tube through an auxiliary yoke. The line broadening by the spot-wobble signal was subjectively optimized for and by the experimenter for each test picture. In general, the line broadening was adjusted such that a minute gap appeared between adjacent lines.

The line-width to line-pitch ratio without line broadening was about 0.33 for the 225-line interlaced picture. The line-width was measured at the half-luminance level of the line profile. The line-width to line-pitch ratio for the other pictures may be determined by

$$LW/LP = 0.33\left(\frac{L_p}{225}\right), \tag{1}$$

where L_p is the number of lines in the picture. Fig. 6 shows line profiles of the scanning lines perpendicular to the direction of scan for an interlaced and noninterlaced picture.

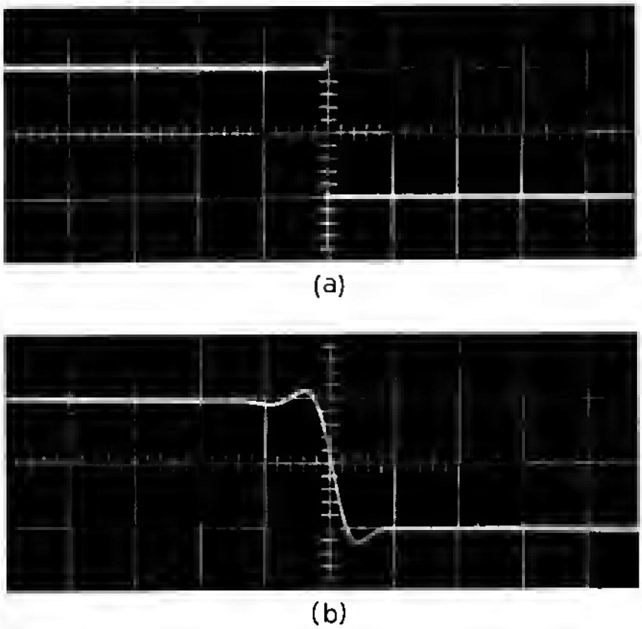


Fig. 5 — Step response of low-pass filter: (a) input to filter, (b) output of filter illustrating 12 percent preshoot and overshoot about step.

Fig. 7 shows line profiles of spot-wobbled scanning lines perpendicular to the direction of scan for an interlaced and noninterlaced picture. (The asymmetry of the spot profile is due to a slight misalignment in the position of the auxiliary yoke.) At the juncture of adjacent lines the luminance level of each line was about 25 percent of its maximum luminance. Since the period between adjacent lines for the interlaced picture is 1/60 second the observer will see the sum of the contributions of each line at their juncture.[2] Therefore, in the spot-wobbled line-interlaced pictures the brightness at the juncture of adjacent lines was about

$$B_j = 1/4(B_1 + B_2), \tag{2}$$

where B_j = brightness at the junction of adjacent lines, B_1 = maximum brightness of line one, and B_2 is the maximum brightness of line two.

The Talbot-Plateau Law[2] says that an observer watching flashing lights above the CFF will sense an apparently constant mean value of the luminance of the lights over the period of the flashes. Equation (2) is a special case of the Talbot-Plateau Law. The law must be expressed

in its complete form to cover the spot-wobbled noninterlaced pictures. The Talbot-Plateau Law is

$$Lm = \frac{1}{T}\int_0^t L\,dt, \tag{3}$$

where Lm is the mean value of the real luminance taken over one period or over any time t comprising an integral number of periods.

With spot-wobbled noninterlaced pictures the period between successive excitations of the phosphor at the juncture of adjacent lines is one line period. Since the phosphor has a finite decay time, it will still be luminescing at the juncture of adjacent lines when excited the second time. Thus, the luminance generated by the second excitation will add to that remaining from the first excitation. The second excita-

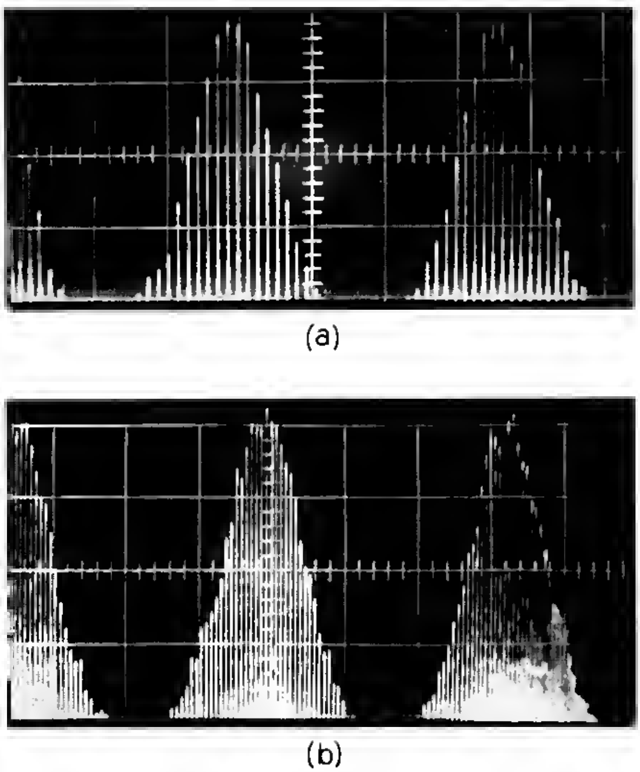
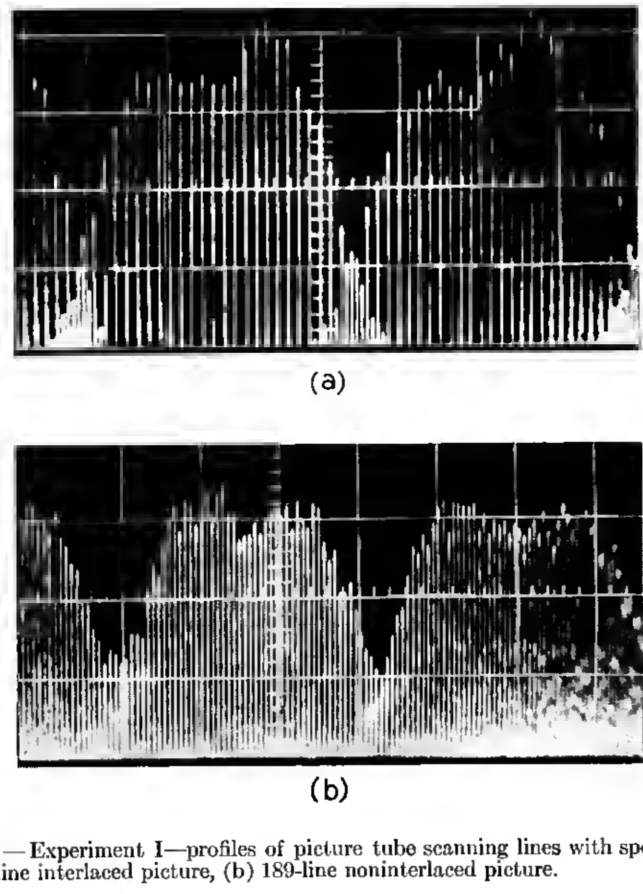


Fig. 6—Experiment I—profiles of picture-tube scanning lines. (a) 225-line interlaced picture with line width to line-pitch ratio of 0.33, (b) 189-line noninterlaced picture with line-width to line-pitch ratio of 0.28.

tion one line period later at the juncture of adjacent lines, according to the Talbot-Plateau Law, increased the mean luminance at the juncture by about 25 percent.

Asymmetrical spot defocussing was obtained by placing two electromagnets about the neck of the picture tube such that they defocussed the scanning spot perpendicular to the direction of line scan only. Another experiment[6] has shown that the preferred line-width to line-pitch ratio for line-interlaced pictures is about 1.7 and for noninterlaced pictures is about 1.2. Fig. 8 shows the effect of defocussing the scanning spot perpendicular to the direction of scan for a line-interlaced picture. When the line-width to line-pitch ratio is 1.7 the luminance contributed by a line at the juncture of adjacent lines is about 82 per-



(a)

(b)

Fig. 7 — Experiment I—profiles of picture tube scanning lines with spot-wobble. (a) 225-line interlaced picture, (b) 189-line noninterlaced picture.

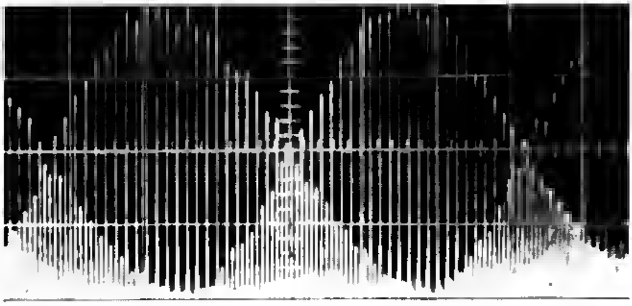


Fig. 8 — Experiment III—profiles of picture tube scanning lines with line-width to line-pitch ratio of 0.9 where the overlap at the juncture of adjacent lines is approximately 50 percent.

cent of the luminance at the center of that line. For a noninterlaced picture with a line-width to line-pitch ratio of 1.2 the luminance contributed by a line at the juncture of adjacent lines is about 60 percent of the luminance at the center of that line. Equations (2) and (3) are also applicable in these cases.

Switching between the A-B pairs was instantaneous in so far as the observer was concerned. Switching between A-B pairs was under the control of the observer. The switching action started with the leading edge of the vertical drive pulse and was completed during the vertical blanking interval so that visible transients were minimized.

The test appartus was checked out twice each day to insure that all apparatus was operating correctly and aligned properly.

The test room, Fig. 9 was a specially constructed room which was remote from the experimenter's station. Audio communication between experimenter and observer was over an intercom. The intercom was a push-to-talk type which permitted noise (switching, etc.) isolation between the test room and experimenter's station.

The observer was seated in a comfortable chair at a distance of about 40 inches from the screen of the monitor. The picture size was 5 inches by 5 inches for each case.

III. TEST PROCEDURE AND INSTRUCTIONS

A-B testing techniques were employed in which one of the pictures was always the interlaced picture. Tbe two pictures were presented in sequential order under the control of the observer.

Once an A-B pair was selected by the experimenter, control of the A-B switch was turned over to the observer. The observer switched

Fig. 9 — Test room.

between the two pictures of the A-B pair at will and for as long as he wished until he reached a decision. After each observer's decision, the experimenter presented to the observer a uniform gray raster set near the average luminance level of the picture during which time the experimenter selected the next A-B pair. Set-up switching time was about 5 seconds.

The oral instructions to each observer were:

"You will be shown 32 sets of pictures to compare. Each set will consist of 2 pictures. The pictures between sets and within sets will be different.

"The A picture will appear when you depress this A button and the B picture will appear when you depress this B button. You may switch back and forth as often as you wish and for as long as you wish.

"Once you have decided which picture you like best, please announce your preference over the intercom as A or B."

Each of the 25 observers made a forced choice decision for one of the two pictures in each of the 32 pairs. The total observation time for observers varied from 15 minutes to 30 minutes.

Question and answer sessions were held after each test session. All of the observers detected the subjective picture defects due to interlacing. Their description of these effects was in terms of noise. It appears that their preferences was an expression of their reaction to the annoying effects of "noise" in the line-interlaced picture.

IV. EXPERIMENTAL DESIGN—EXPERIMENT I

The objective was to determine subjectively how much saving in bandwidth a line-interlaced picture provides with respect to a non-interlaced picture. The most straightforward experimental design was the Method of Constant Stimuli[7] in which the constant (or reference) picture was a line-interlaced picture which was compared with several noninterlaced pictures with different numbers of lines and bandwidths. The noninterlaced pictures provided a physical scale on which a point of subjective quality (PSE) could be estimated for the interlaced picture.

A 225-line picture was selected as the reference interlaced picture. This picture (as well as the noninterlaced pictures) was displayed on a 5 inch $\times$ 5 inch raster. At this picture height and a viewing distance of 40 inches, tbe 225-line interlaced picture had an angular subtense between adjacent lines of 2.2 minutes of arc (see Table I). Four non-interlaced pictures were used starting with a 225-line picture and decreasing in steps with ratios of $\sqrt[4]{2}$ to a 135-line picture, Fig. 10.

Two levels of noise were introduced as test variables. The first or zero level was that introduced by the test apparatus. Most of this noise, just above threshold, was contributed by the vidicon camera. The second or added noise had a Gaussian distribution. The peak-to-

Table I — Some Parameters of Experimental Apparatus (Experiment I)

Number of lines	Line-interlace	Horizontal sweep rate (Hz)	Band-width (MHz)	Picture elements/frame	Visible picture elements/frame	Visible picture ele-ments/line	Angular subtense between two lines at 40″
225	Yes	6750	0.575	38,333	28,366	142	2.2′
225	No	13,500	1.154	38,466	28,366	142	2.2′
189	No	11,340	0.812	27,066	20,029	119	2.5′
162	No	9720	0.575	19,166	14,183	102	2.9′
135	No	8100	0.413	13,766	10,186	85	3.4′

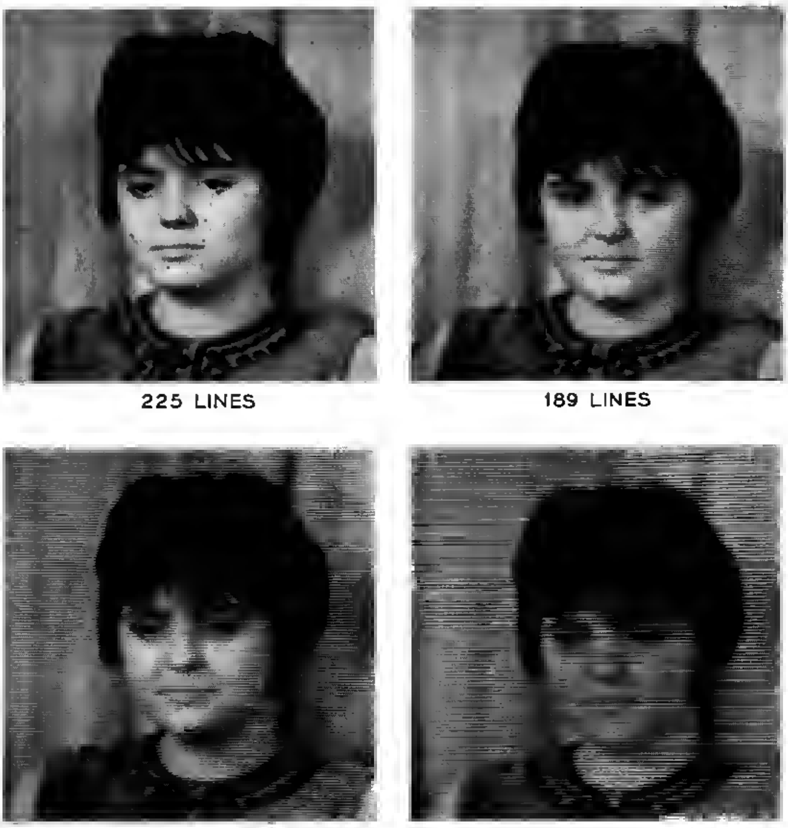
peak picture signal to added rms noise level was set at 30 dB for the interlaced picture with a bandwidth of 575 kHz. For the noninterlaced pictures, the peak-to-peak picture signal to rms noise was

$$S/N = 30\,\text{dB} - 10 \log \frac{Bw}{575\text{kHz}} \tag{4}$$

where Bw is the bandwidth of the noninterlaced picture. (See Table II).

Two levels of illumination were used 25 fc (275 lm/m^2) and 50 fc (550 lm/m^2). Although the luminance was not adjusted it varied with illumination as follows:

Illumination	High-light luminance	Low-light luminance	Contrast ratio
25 fc (275 lm/m^2)	100 fL (340 cd/m^2)	9 fL (30 cd/m^2)	11 : 1
50 fc (550 lm/m^2)	105 fL (360 cd/m^2)	20 fL (70 cd/m^2)	5 : 1



225 LINES

189 LINES

162 LINES

135 LINES

Fig. 10 — Photographs of noninterlaced pictures.

Table II — Experiment I: Frequency of Preference for Noninterlaced Pictures over 225-Line Interlaced Picture for the Various Conditions of the Test

	Additional variables	$\bar{N}$–$\overline{SW}$–$\bar{I}$	N–$\overline{SW}$–$\bar{I}$	$\bar{N}$–SW–$\bar{I}$	N–SW–$\bar{I}$	$\bar{N}$–$\overline{SW}$–I	N–$\overline{SW}$–I	$\bar{N}$–SW–I	N–SW–I	Summed over all variables
	Number of test sets	25	25	25	25	25	25	25	25	200
Number of lines (noninterlaced)	135	1	1	3	1	1	1	3	2	13
	162	10	14	13	10	12	11	17	15	102
	189	23	20	25	21	23	22	22	18	174
	225	25	25	25	25	25	25	25	24	199

$\bar{N}$ = System noise

N = Signal/noise —
- 135 lines noninterlaced = 31.4 dB
- 162 lines noninterlaced = 30.0 dB
- 189 lines noninterlaced = 28.6 dB
- 225 lines noninterlaced = 27.0 dB
- 225 lines interlaced = 30.0 dB

$\overline{SW}$ = no spot-wobble
SW = spot-wobble
$\bar{I}$ = illumination of 25 fc (275 lm/m²)
I = illumination of 50 fc (550 lm/m²)

The change in luminance is due to the change in the amount of reflected light from the safety glass with a change in the illumination. Subsequent measurements of the low-light luminance indicated the 20 fL (70 cd/m^2) measurement is probably in error on the high side.

Spot-wobble was introduced at the picture tube as another variable. Fig. 11 illustrates the effect of spot-wobble on the received picture.

Two types of observers, skilled and nonskilled, were used in the test. Skilled observers were considered those who work in the television engineering field. Nonskilled observers were considered those whose only prior experience was home viewing of their commercial receivers. Thirteen skilled and twelve nonskilled observers were used.

Two young women were used as models. One was blonde with fair

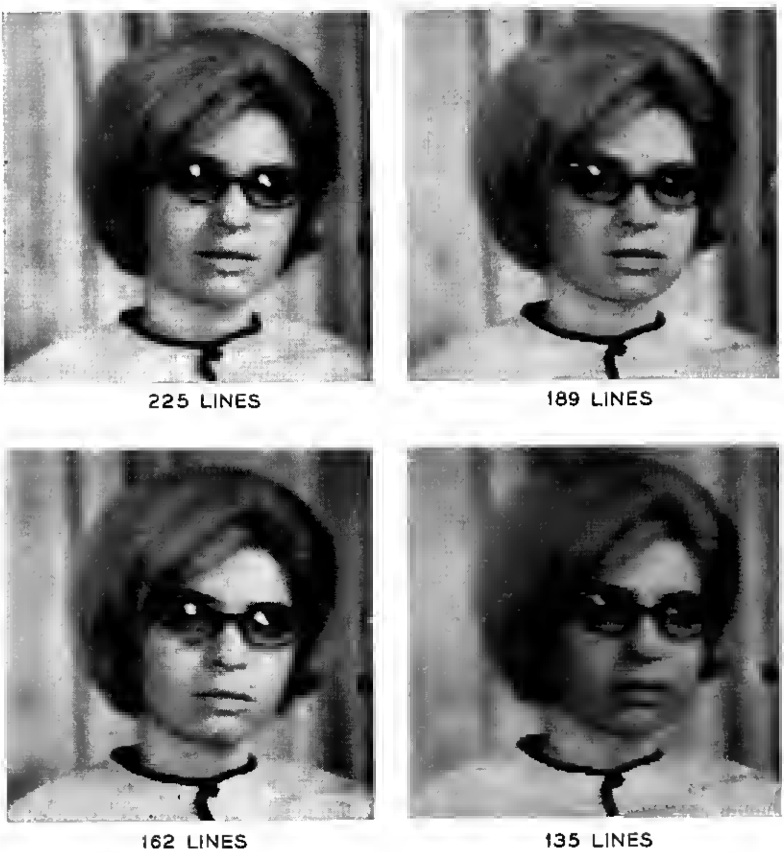


Fig. 11 — Photographs of noninterlaced pictures with spot-wobble.

complexion who wore black horn-rimmed glasses and the other was brunette with dark complexion. During the test, the models pantomimed what might be considered a face-to-face conversation. Subjective line-pairing, not investigated in this experiment, was minimized by instructing the models not to make rapid movements or movements which were perpendicular to the scanning lines. The observers were partially immobilized in the same sense by requiring them to operate the A-B switch whose position was fixed. The observers were not cautioned as to their movements otherwise. Fig. 10 shows the brunette model for the four noninterlaced pictures. Fig. 11 shows the blonde model for the four noninterlaced pictures with spot-wobble. The 225-line interlaced picture is not shown since photographically it would appear the same as the 225-line noninterlaced picture.

The order in which the interlaced picture and the noninterlaced pictures appeared in the A-B positions on the buttons was determined by a random number table.

Each observer saw 32 A-B pairs where each pair consisted of the interlaced picture and one of the 4 noninterlaced pictures. When used, the additional variables noise, spot-wobble, illumination and combinations thereof were added to both pictures of the A-B pair. The order of presentation of the noise and spot-wobble variables was also randomized with random number tables. The level of illumination was set at one value during the first half of each session and set at the other value during the second half of each session. Successive observers started their test session with alternate levels of illumination.

Seven of the skilled observers and six of the nonskilled observers saw the blonde model and six of each saw the brunette model.

V. EXPERIMENT I—RESULTS AND CONCLUSIONS

Table II lists the ferquency of preference for the noninterlaced pictures over the 225-line interlaced picture for the variables employed in this experiment.

In the tables and the text, the response data is generally related in terms of the number of noninterlaced lines, whereas the objective is to determine the bandwidth savings of interlaced pictures over noninterlaced pictures. However, on the data graphs the ordinate of the curves is expressed in terms of the number of noninterlaced lines, Ln, and the bandwidth improvement ratio with line-interlace, Bi. The reference for the bandwidth improvement factor is a hypothetical 159-line noninterlaced picture with a bandwidth of 575 KHz. The number of noninterlaced lines, Ln, may be converted to bandwidth

improvement ratio with line-interlace, Bi, by

$$Bi = \frac{Ln^2}{159^2}. \tag{5}$$

The frequency of preference data listed in Table II was converted to percentiles. On the hypothesis that the percentile score was cumulative normal a maximum likelihood probit[8] regression line was computed for each set of data. A χ^2 test was performed on each of the regression lines. Since none of the χ^2 values exceeded the value of the number of degrees of freedom less one, there appears to be no conflict with the hypothesis that the data is cumulative normal.

The probit regression line and the original data points are plotted on each of the graphs.* In addition, the following information is listed in tabular form on each graph, (*i*) the point of subjective equality (PSE) in terms of number of noninterlaced lines, (*ii*) the standard deviation of the distribution, σ, and (*iii*) the standard error of the PSE, SEP.†

The method of the standard error of the difference[9] was used in determining the significance of a difference between two PSE's in the following manner. The standard error of the difference between two independent random variables, is equal to the square root of the sum of their variances. Therefore, assuming independence,

$$\sigma_{\text{PSE}} = \sqrt{\text{SEP}_1^2 + \text{SEP}_2^2}\,, \tag{6}$$

where σ_{PSE} is the standard error of the difference between PSE's and SEP^2 is the variance of the PSE's. The χ^2 test indicated no conflict with the hypothesis that the PSE's are from a normal distribution, thus the distribution of the difference between the distributions of the curves from which the PSE's will be drawn is normal.

The test for significance was made in terms of T which is the difference between the PSE's expressed in terms of σ_{PSE} as

$$T = \frac{|\,\text{PSE}_1 - \text{PSE}_2\,|}{\sigma_{\text{PSE}}}. \tag{7}$$

Adopting a null hypothesis that the two PSE's belong to the same parent distribution, we may set our confidence limits at a probability level of 0.05. Thus, a value of the normal deviate T of 1.96 or greater will indicate a significant difference between two PSE's.

* When data points are missing from the data plots they represent a zero or 100 percentile score, which is not visible on the graphs.

† Each of these values are weighted best estimates. Finney, Ref. 8, gives an excellent description of the statistical techniques used in arriving at these values.

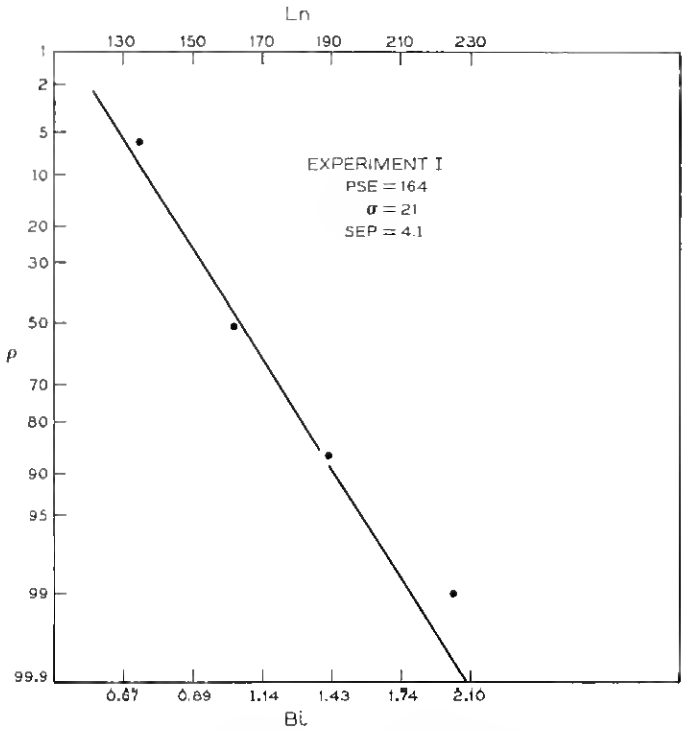


Fig. 12 — Experiment I—the preference for noninterlaced pictures over a 225-line interlaced picture summed over all additional variables.

The preference percentile scores for the four noninterlaced pictures over the interlaced picture summed over all additional variables is plotted in Fig. 12. The PSE of the 225-line interlaced picture with respect to the noninterlaced picture is approximately a 164-line picture (Bi = 1.06) with a standard deviation of about 21 lines and a SEP of 4.1 lines.

Significant first-order interactions between the additional variables was found only between the spot-wobble and added noise variables. This interaction is illustrated in Fig. 13 where curves of the preference percentile scores versus number of noninterlaced lines for spot-wobble without added noise summed over the other variables and spot-wobble with added noise summed over the other variables is plotted. The PSE for spot-wobble without added noise is a 157-line picture (Bi = 0.98) whereas for spot-wobble with added noise the PSE is a 167-line picture

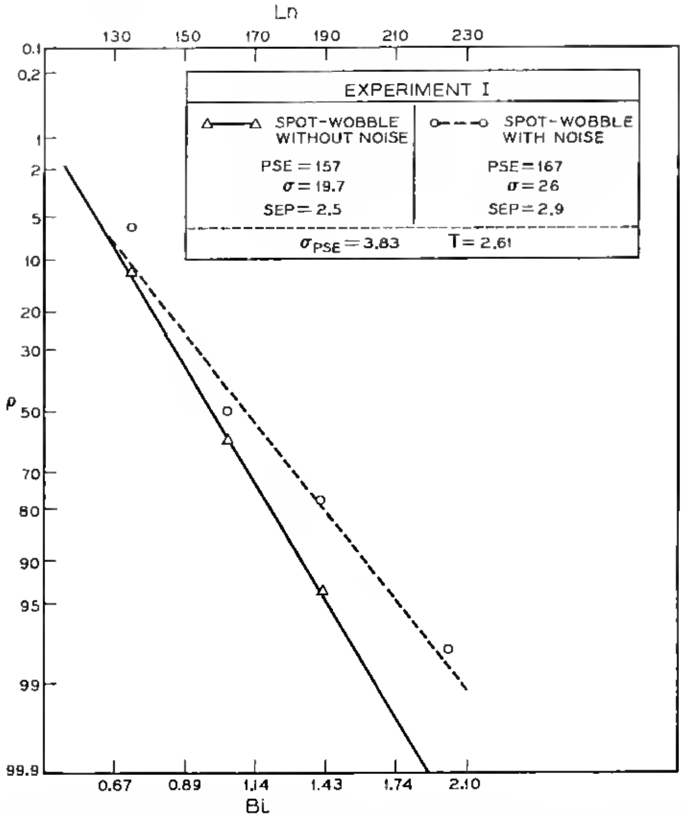


Fig. 13 — Experiment I—the preference for noninterlaced pictures over a 225-line interlaced picture with spot-wobbled picture-tube scanning beam: (a) without added noise, and (b) with added noise. (Summed over all additional variables.)

(Bi = 1.10). A T-score of 2.61 indicates there is a significant interaction between noise and spot-wobble.

The first-order interaction between spot-wobble and noise precludes a check on the main effects of these two variables summed over the other. Therefore, the interacting variable must be eliminated in the analysis of their main effects. Fig. 14 shows the preference percentile score of the noninterlaced pictures over the interlaced picture for three cases, (*i*) summed over all additional variables except spot-wobble and added noise, (*ii*) spot-wobbled scanning beam summed over all additional variables except added noise (also shown in Fig. 13), and (*iii*) added noise summed over all additional variables except spot-

wobble. The results are itemized below:

	Case 1	Case 2	Case 3
PSE	165	157	166
Bi	1.08	0.98	1.09
σ	17	20	20
SEP	5.1	2.5	5.6

A *T*-score of 1.4 for case 1 versus case 2 indicates that spot-wobbling of the scanning beam does not significantly effect the results. Also the

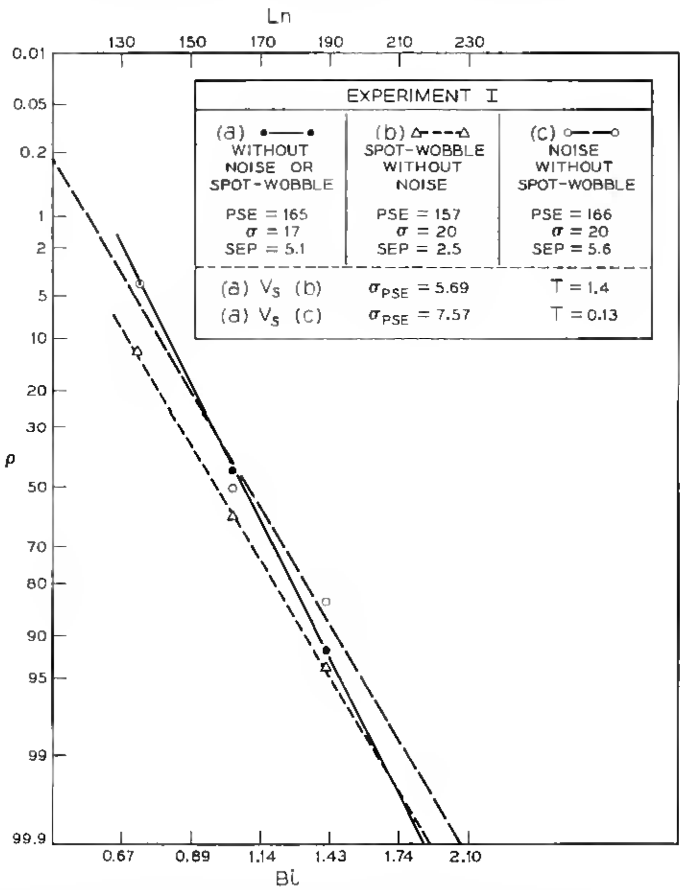


Fig. 14 — Experiment I—the preference for noninterlaced pictures over a 225-line interlaced picture: (a) summed over all additional variables except added noise and spot-wobble, (b) spot-wobbled picture-tube scanning beam, summed over all additional variables except noise, and (c) added noise summed over all additional variables except spot-wobble.

T-score of 0.13 indicates that added Gaussian noise does not significantly effect the results.

Spot-wobbling the scanning beam of a noisy picture increases the visible size of the noise which is analogous to lowering tbe frequency of the noise. It is a well-known fact that low frequency noise is more detrimental to the quality of a television picture than high frequency noise. When the pictures were spot-wobbled without added noise, the PSE was 157 lines indicating a strong preference for the noninterlaced pictures in this case. When noise was added to the spot-wobbled pictures, there was an increase in the preference for the line-interlaced picture, PSE = 167 lines. This indicates that a combination of noise and spot-wobble is more detrimental to the quality of a noninterlaced picture than a line-interlaced picture by a significant amount. Interline flicker associated with the line-interlaced picture appears subjectively as noise to the observer. Could it be that the added noise in a spot-wobbled picture is partially confounded with the interline-flicker of the line-interlaced picture and therefore is not as visible as such as it is in the noninterlaced pictures?

Fig. 15 shows graphs of the preference percentile scores for the noninterlaced pictures over the interlaced picture for two levels of illumination summed over the additional variables. A significant difference was not detected for the change in illumination. Thus, one may conclude that a change in illumination will not change the subjective equivalency between line-interlaced and noninterlaced television pictures under the conditions of this experiment.

Fig. 16 shows the preference percentile score of the noninterlaced pictures over the interlaced picture for the skilled observers and the nonskilled observer. The PSE for the skilled observers is a 166-line picture (Bi = 1.09) with a standard deviation of 21 lines. The PSE for the unskilled observers is a 163-line picture (Bi = 1.05) with a standard deviation of 21 lines. A T-score of 0.37 indicates there is no significant difference between the two groups of observers. However, an interesting significant difference was found within the skilled group of observers. The skilled observers were drawn from two television engineering groups at these laboratories which work more or less independently of each other. One group had a significantly stronger preference for the line-interlaced picture than the other. Yet when the data of the two groups were pooled the PSE of the skilled group and the PSE of the nonskilled group were not significantly different. This implies that when conducting subjective tests of this type where the results are applicable to a lay population, the possibility of a strong bias in a skilled group should not be overlooked.

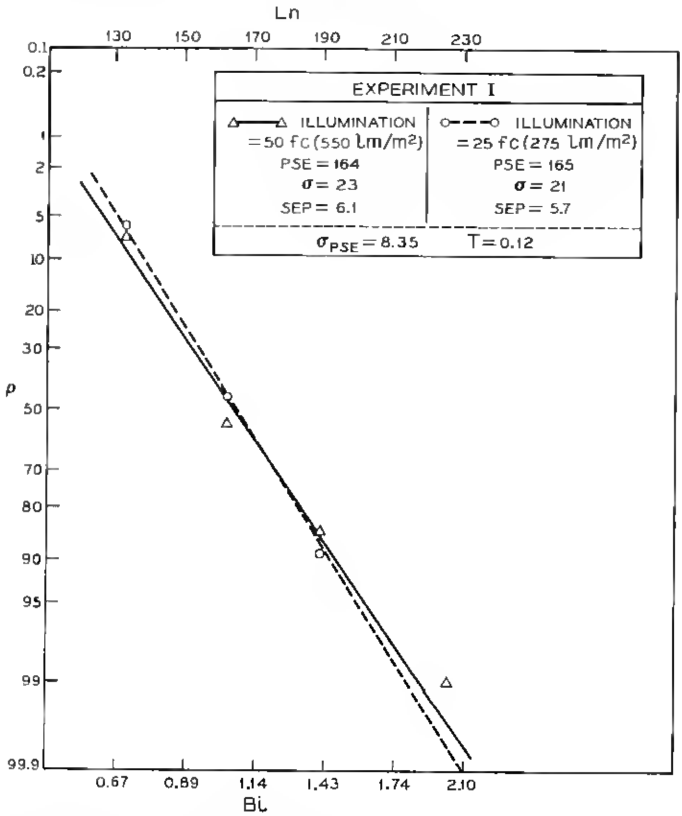


Fig. 15 — Experiment I—the preference for noninterlaced pictures over a 225-line interlaced picture at two levels of illumination. (Summed over other additional variables.)

Fig. 17 shows the preference percentile score of the noninterlaced pictures over the interlaced picture for the blonde model is a 165-line picture (Bi = 1.08) with a standard deviation of 19 lines. The PSE of the brunette model is a 163-line picture (Bi = 1.05) with a standard deviation of 23 lines. Their T-score of 0.24 indicates there is no significant difference in their PSE's.

VI. EXPERIMENT II—EXPERIMENTAL DESIGN

The results obtained in experiment I indicate that the precision of estimation of the PSE could be improved by decreasing the step-size between the noninterlaced pictures. Accordingly, the ratio of the step-size in terms of number of lines between the noninterlaced pictures

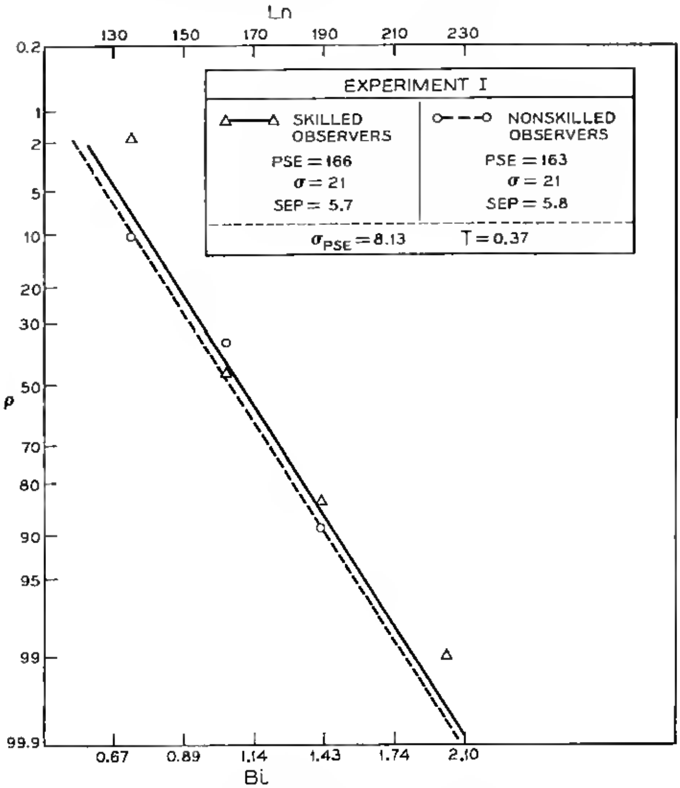


Fig. 16 — Experiment I—the preference for noninterlaced pictures over a 225-line interlaced picture for skilled and nonskilled observers. (Summed over all variables.)

was reduced to $\sqrt[9]{2}$ over the range of 135 lines to 189 lines. Table III shows these parameters and the values of the other parameters which were changed in order that the picture format would be consistent with the change in number of lines.

Another variable of importance, a change in picture luminance, was introduced at two levels in experiment II. These two levels were:

	Case I	Case II
High Light	80 fL (270 cd/m²)	50 fL (170 cd/m²)
Low Light	3.5 fL (12 cd/m²)	1.5 fL (5 cd/m²)
Contrast Ratio	23 : 1	33 : 1
Illumination	50 fc (550 lm/m²)	25 fc (275 lm/m²)

The ambient illumination was set at the two levels indicated in the table which the experimenter thought gave good picture rendition in

each case. It was felt that this was legitimate since experiment I indicated that a change in illumination did not significantly affect the PSE.

In addition to determining the PSE of the line-interlaced picture with respect to the set of noninterlaced pictures for the conditions cited above, it was desirable to determine the subjective relationship between the noninterlaced pictures. Accordingly, an incomplete factorial design was used where the line-interlaced picture was compared with each of the noninterlaced pictures and the adjacent (in terms of number of lines) noninterlaced pictures were compared with each other. A-B testing techniques were employed again. The order of A-B pairs and the order within A-B pairs was determined by random number tables.

The test apparatus described earlier was used except that it was modified to accommodate the new rates.

In case I, 12 nonskilled observers were used with two replications each. In case II, 9 nonskilled subjects were used with three replications each.

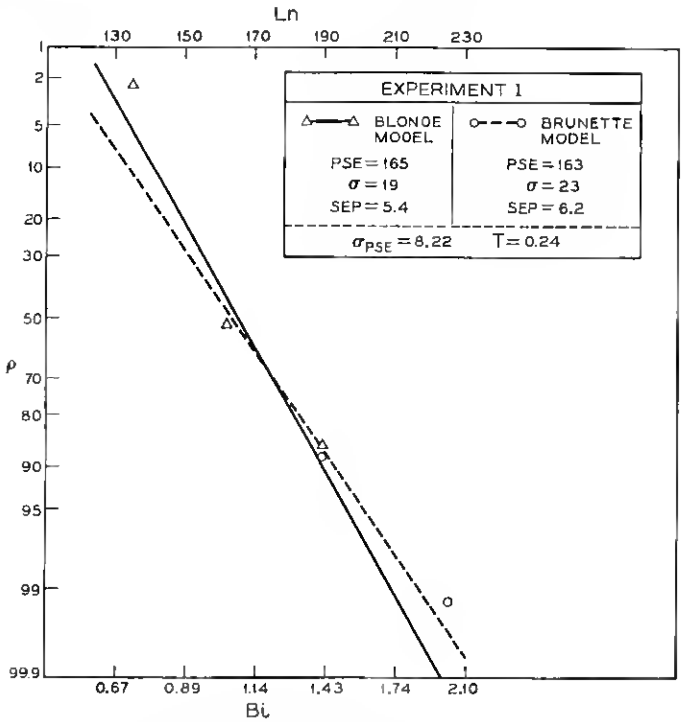


Fig. 17 — Experiment I—the preference for noninterlaced pictures over a 225-line interlaced picture for blonde and brunette models. (Summed over all variables.)

The test procedure and instructions to the observer were the same as those described in Section IV except for the necessary change in the number of "sets of pictures".

VII. EXPERIMENT II—RESULTS AND CONCLUSIONS

Each of the observers made a forced choice decision for one of the two pictures in each A-B pair presented to him. In addition to recording his preference, the time it took each observer to reach a decision was recorded for each A-B pair. It was assumed that time would vary proportionately with the difficulty of reaching a decision, i.e., time would be well correlated with the first derivative of the percentile score.

Table III—Some Parameters of Experimental Apparatus (Experiment II)

Number of lines	Line-interlace	Horizontal sweep rate (Hz)	Band-wdth (MHz)	Picture elements/frame	Visible picture elements/frame	Visible picture ele-ments/line	Angular subtense between two lines at 40″
225	Yes	6750	0.575	38,333	28,366	142	2.2′
189	No	11,340	0.812	27,066	20,029	119	2.5′
175	No	10,500	0.695	23,166	17,143	110	2.7′
162	No	9720	0.575	19,166	14,183	102	2.9′
147	No	8820	0.495	16,500	12,210	92	3.2′
135	No	8100	0.415	13,766	10,186	85	3.4′

Using time as the variable, control charts[10] were set up for the experiment. The control charts for the mean time indicated that the experimental apparatus was under control at all times. Range control charts indicated that all of the observers were within population control limits.

Table IV (a) lists the frequency of preference for the noninterlaced pictures over the 225-line interlaced picture for the two levels of luminance. Listed in Table IV (b) is the preference of the noninterlaced picture with the larger number lines over the adjacent noninterlaced picture with the lesser number of lines.

The data listed in Table IV (a) relating the interlaced picture to the noninterlaced pictures was converted to percentile scores and plotted on uormal-probability paper as shown in Fig. 18.* Again assuming

* When the fifth data point is missing from the graph, it occurred at the 100th percentile for the 225-line noninterlaced picture.

Table IV — Experiment 11

(a)

Frequency of preference for noninterlaced pictures over 225-line interlaced picture

	Case	I	II
	No. of observers	12	9
	Replications	2	3
Number of lines (non-interlaced pictures)	189	22	24
	175	12	10
	162	7	2
	147	1	1
	135	2	0

(b)

Noninterlaced pictures: frequency of preference for picture A over picture B in terms of number of lines

Case		I	II	Total out of 51 observations
No. of observers		12	9	
Replications		2	3	
Pix A	Pix B			
189	175	22	26	48
175	162	22	26	48
162	147	21	23	44
147	135	21	26	47

a normal distribution, a probit regression line was determined for each case. Chi-square tests indicated no conflict with the hypothesis of a normal distribution.

The data of experiment II was tested for significance in the same manner of experiment I.

For a high-light luminance of 50 fL (170 cd/m^2) the PSE was a 177-line noninterlaced picture ($Bi = 1.24$) with a σ of 12 lines and a SEP of 2.0 lines. For a high-light luminance of 80 fL (270 cd/m^2), the PSE was 171 line noninterlaced picture ($Bi = 1.16$) with a σ of 18 lines and a SEP of 2.6 lines.

In addition to the graphs of experiment II, Fig. 18 shows the graph of the results from experiment I (see Fig. 12) for a high-light luminance of about 100 fL (340 cd/m^2) summed over all variables. Thus, three values of high-light luminance are available in checking for a significant difference between high-light luminances.

The T-score for changes in high-light luminances of 50 fL (170 cd/m^2) to 80 fL (270 cd/m^2) and 80 fL (270 cd/m^2) to 100 fL (340 cd/m^2) is 1.83 and 1.44, respectively. These T-scores approach the significant value of 1.96. Thus, we may conclude that a change in high-light luminance of less than 30 fL (100 cd/m^2) over the range of 50 fL (170 cd/m^2) and 100 fL (340 cd/m^2) will not quite produce a significant difference in the PSE when comparing line-interlaced and

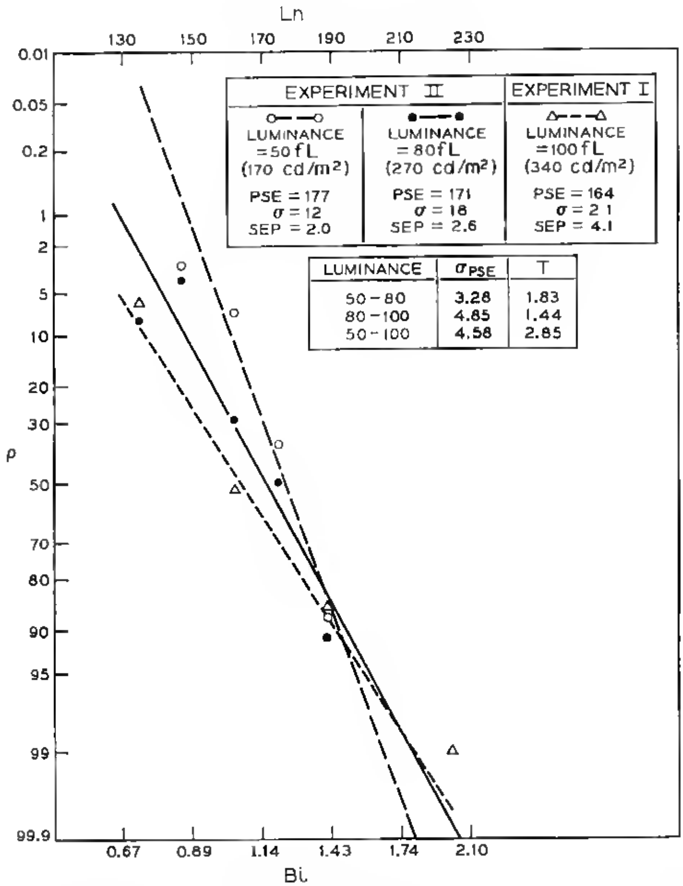


Fig. 18 — Experiment I and II—the preference for noninterlaced pictures over a 225-line interlaced picture for three levels of luminance.

noninterlaced television pictures under the conditions of these experiments.

The T-score for a change in high-light luminance of 50 fL (170 cd/m^2) to 100 fL (340 cd/m^2) is 2.85. This value of T is highly significant. We may conclude that a change in high-light luminance from 50 fL (170 cd/m^2) to 100 fL (340 cd/m^2) will produce a highly significant difference in the PSE when line-interlaced and noninterlaced television pictures are compared under the conditions of these experiments.

The preference of the noninterlaced picture with the larger number of lines over the adjacent noninterlaced picture with the lesser number of lines is not shown in graphic form. Table IV-B shows that about

90 percent of the observers preferred the pictures with the larger number of lines over the picture with the lesser number of lines. The exact meaning of these results is not obvious. Although the observers were asked to make their decisions on the basis of picture quality, we may instead have a measure of the observers ability to detect a difference in the number of lines between two pictures.* In other words, the observer in detecting which picture had the greater number of lines, may have assumed that this picture must also have the better quality. We may conclude that about 90 percent of the observers will be able to determine which of two noninterlaced television pictures has the greater number of lines when the ratio of the number of lines in the picture is $\sqrt[9]{2}$ over the range of 135-line pictures to 225-line pictures.

VIII. EXPERIMENT III—EXPERIMENTAL DESIGN

The fact that the image of a television picture is reproduced in lines on the picture tube screen is objectionable to most people. This is particularly true of low-resolution television systems with coarse line structures. Broadening of the scanning lines will aid in reducing the objectionable effects of the line structure. Asymmetrical defocussing of the scanning spot with a magnet attached to the neck of the picture tube is one of the most economical approaches to this problem though Monteath[11] has shown that it is not the best esthetic solution.

Asymmetrical spot defocussing was used in this experiment as described in Section II. The line-width to line-pitch ratio was set at approximately 1.7 for the interlaced picture and approximately 1.2 for the noninterlaced pictures.[6] Fig. 19 shows photographs of a line interlaced and noninterlaced picture with the line-width to line pitch ratios set for the preferred values.

The 225-line interlaced picture was compared with the five noninterlaced pictures described in Table III except that the 225-line noninterlaced picture described in Table I was exchanged for the 135-line noninterlaced picture of Table III.

Two levels of luminance and illumination were introduced as follows:

	Case I	Case II
High-Light	60 fL (200 cd/m²)	40 fL (140 cd/m²)
low-Light	3.5 fL (12 cd/m²)	1.5 fL (5 cd/m²)
Contrast Ratio	17.2 : 1	27.4 : 1
Illumination	100 fc (1100 lm/m²)	50 fc (550 lm/m²)

* The experimenter found that the change in the number of lines (about 9 percent) was quite evident in each case, whereas the change in bandwidth (about 18 percent) was difficult to detect. Baldwin,[6] found that a change in bandwidth of 16 percent was not perceptible in his experiments.

(a)

(b)

Fig. 19 — Experiment III—photographs of asymmetrically defocussed pictures. (a) 225-line interlaced picture, (b) 225-line noninterlaced picture.

On the assumption that a change in illumination did not have a significant effect on the PSE, the illumination was changed to give good picture rendition with the levels of luminance used.

The order of presentation of A-B pairs for each case and the order within pairs was determined hy random numher tables.

In case I, 16 nonskilled ohservers were used with 3 replications each. In case II, 15 nonskilled ohservers were used with 3 replications each.

The test procedure and instructions to the observers were the same as those descrihed in Section IV except for the necessary change in the "numher of sets of pictures."

IX. EXPERIMENT III—RESULTS AND CONCLUSIONS

Each of the observers made a forced choice decision for one of the two pictures in each A-B pair presented to him. In addition to recording his preference, the time it took each observer to reach a decision was recorded for each A-B pair.

Using time as the variable, control charts[10] were set up for the experiment. The control charts for the mean time indicated that the experiment was under control at all times. Range control charts indicated that all of the observers were within population control limits.

Table V lists the frequency of preference of the noninterlaced pictures over the 225-line interlaced picture for the two cases under test.

The data listed in Table V was converted to percentile scores and plotted on normal-probability paper as shown in Fig. 20. Assuming a normal distribution, a probit regression line was determined for each case. Chi-square tests indicated no conflict with the hypothesis of a normal distribution.

For case I with a bigh-light luminance of 60 fL (200 cd/m^2) the PSE was a 173-line picture (Bi = 1.18) with a σ of 22 lines and a SEP of 2.1 lines. For Case II with a high-light luminance of 40 fL (140 cd/m^2) the PSE was a 186-line noninterlace picture (Bi = 1.37) with a σ of 19 lines and a SEP of 2.3 lines. The value of the quantity T was 3.75 indicating a significant difference between the two PSE's.

We may conclude that when the line-width to line-pitch ratio is set at its preferred value for interlaced and noninterlaced television

TABLE V — EXPERIMENT III: FREQUENCY OF PREFERENCE FOR NONINTERLACED PICTURES OVER 225-LINE INTERLACED PICTURE WHEN THE LINE-WIDTH TO LINE-PITCH RATIO IS 1.7 FOR INTERLACED PICTURES AND 1.2 FOR NONINTERLACED PICTURES

	Case	I	II
	No. of observers	16	15
	Replications	3	3
Number of lines (noninterlaced pictures)	225	47	45
	189	45	25
	175	28	10
	162	13	4
	147	9	3

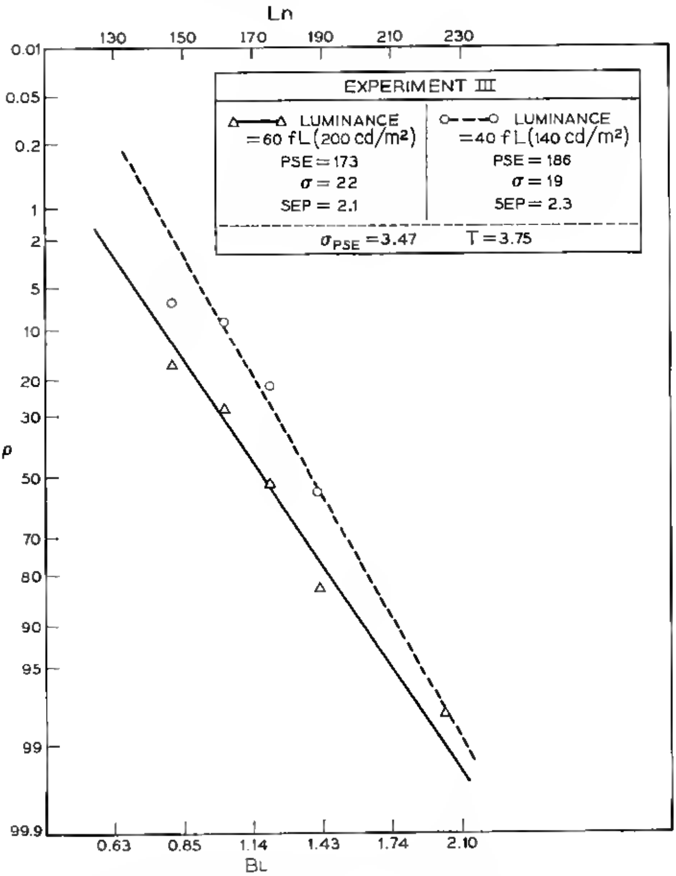


Fig. 20 — Experiment III—the preference for noninterlaced pictures over a 225-line interlaced picture for two levels of high-light luminance with the line-width to line-pitch ratio set to its preferred value.

pictures there will be a significant difference in the PSE when the high-light luminance is changed from 60 fL (200 cd/m^2) to 40 fL (140 cd/m^2) or vice versa under the conditions of this experiment.

X. SUMMARY AND CONCLUSIONS

It has been found that the line interlacing of low-resolution television pictures provide the observer with substantially less than a 2 : 1 savings in bandwidth under the conditions of these experiments. In the most optimistic case where the high-light luminance was 40 fL (140 cd/m^2)

and in which the line-width to line-pitch had been optimized the subjective bandwidth savings was about 37 percent.

It was found that high-light luminance had a significant effect on the subjective equivalence between line-interlaced and noninterlaced television pictures. In the worst case with a high-light luminance of 100 fL (340 cd/m^2) the line-interlacing of a 225-line television picture provided a savings in subjective bandwidth of about 6 precent. Under similar test conditions at a high-light luminance of 50 fL (170 cd/m^2), the subjective bandwidth savings was about 24 percent.

The main effects of the variables added Gaussian noise, spot-wobble illumination, two types of models, and two types of observers did not produce a significant difference in their results. The first-order interaction between each of these variables with the exception of noise and spot-wobble was not significant.

A significant first-order interaction was found between added Gaussian noise and a sinusoidally spot-wobbled scanning beam. When the scanning beam of the test pictures was spot-wobbled with a 7.14-MHz sine wave, the 225-line interlaced picture did not provide any subjective savings in bandwidth. However, when noise with a Gaussian distribution was added to the spot-wobbled picture the subjective bandwidth savings was about 10 precent. This indicates that added noise is more detrimental to the quality of a spot-wobbled noninterlaced picture than to a spot-wobbled line-interlaced picture.

It was found that about 90 percent of the observers preferred the noninterlaced picture with the greater number of lines when the ratio of the number of lines of the two pictures was $\sqrt[9]{2}$ and the vertical resolution in each picture was approximately equal to the horizontal resolution.

The same amount of picture information is presented in both the 225-line interlaced picture and the 225-line noninterlaced picture. The noninterlaced picture is a quiet picture in which the small details may be easily detected and tracked by the observer. This same detail is visible in the interlaced picture, but the observer must look "through" the interline flicker effects and resist the intrinsic desire of the eye to track stroboscopic patterns in order to see the detail. It is highly probable that the results of this experiment would have been quite different if the observers task was to recognize and identify fine detail, such as the recognition and identification of alphanumerical material.

In the design of a low-resolution television system the choice between line-interlace and noninterlace is not completely resolved by these experiments. These experiments provide us with a long awaited measure

of the subjective equivalence betweeu line-interlaced and noninterlaced television pictures under the conditions described. Before a final decision is made many other factors such as cost of implementation, the subjective effects of PCM processing, repeater spacing, the subjective effects of crosstalk, etc. if applicable, must be considered. Finally, although the full benefits of a 2:1 savings in bandwidth is not realized by line-interlacing it does provide some bandwidth savings in all of the cases studied except one and furthermore, line-interlacing appears to partially mask the affects of added noise.

XI. ACKNOWLEDGMENTS

Most of the members of the Visual Systems Research Department of Bell Laboratories have made some contribution to this experiment. W. T. Wintringham has directed and assisted this experiment from its beginning. J. A. Murphy and F. C. Bollwage designed and built the display terminal. Consultations with P. D. Bricker, M. W. Baldwin, Jr., C. C. Cutler, B. Prasada, and H. Levitt were most helpful in the design and analysis of the experiment.

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